

An evolutionary analysis of economic hubs and transmission mechanisms for wastewater discharge

Xuefeng Li^{1,2*}

1 Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Zhongguancun East
2 Road No. 55, Beijing, 100190, People's Republic of China

3 2 University of Chinese Academy of Sciences, 19 A Yuquan Road, Shijingshan District,
4 Beijing, 100049, People's Republic of China

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9 **Abstract:** Due to the destruction of aquatic ecology and pollution of the water environment, policy
10 formulation needs to pay more attention to factors other than economic benefits. Past research mainly
11 relied on the average propagation lengths (APL) of wastewater discharge to empirically analyze the
12 wastewater propagation between sectors. The hub sectors of wastewater discharge, which are densely-
13 connected to other sectors, play key roles in reflecting wastewater discharge or wastewater treatment
14 in the overall economic system. However, there is current ambiguity deficiency in analytic results of
15 economic hubs and transmission mechanisms of wastewater discharge. At the same time, analyzing
16 the transmission mechanism of wastewater discharge, proposing wastewater management and
17 containment strategies are essential to sustainable development of water resource. This paper
18 calculates the wastewater discharge APL based on the compiled sequential water input-occupancy-
19 output tables of 49 sectors for 2002, 2007, 2012 and 2017 in China. Then, we introduce more broadly
20 marginal dependence linkages into APL. A coupled model named APL-HCG (APL with hub
21 covariance graph) is proposed to analyze the hub wastewater discharge sectors and hub propagation
22 chains overall. The results illustrate the evolutionary pattern of the hub sectors of wastewater
23 discharge and the transmission mechanism implicit in the key wastewater propagation chains
24 nationwide from 2002 to 2017.

25 **Keywords:** wastewater; input-occupancy-output; average propagation lengths (APL); hub sector of
26 wastewater discharge; hub covariance graph (HCG) model

1 Introduction

27 Under the background of Chinese economy entering a new development trajectory, the
28 environmental issues to sustainable economic development has received increasing attention,
29 including topics about water resource. Water is closely related to people's production and life.
30 Resulting from severe water exploitation in production and life, water pollution and water shortage
31 emerged. They have become some of the most important aspects affecting the sustainable
32 development of economy, society and environment. Therefore, analyzing issues about utilization of
33 water resource, wastewater discharge and wastewater treatment are urgent. It needs essential research
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36 to alleviate the influence of wastewater on the sustainable development of economy, society and
37 environment.

38 Sectors or industries are directly or indirectly connected to each other by wastewater propagation.
39 Wastewater discharge average propagation lengths (APL) possess the ability to depict intrinsic
40 economic connections between sectors. The idea of APL is firstly proposed by Dietzenbacher et al.
41 (2005; 2007). It has been adopted to study the impact of fragmentation to economic complexity of
42 Chicago (Luna et al., 2009), the measurement of upstream sectors (Antras et al., 2012), the production
43 chains discovery and evolutionary process of agricultural production chains (Deng and Chen, 2008;
44 2009), the important coefficients in APL matrix (Lu and Xu, 2013) and the grouped APL (Chen, 2014)
45 and so on. Tu et al. (2017) used the APL model to analyze and evaluate wastewater propagation
46 chains in Jing-Jin-Ji region. Wastewater APL's type of economic connections construct wastewater
47 propagation network. Some sectors are more broadly associated with other sectors, or there are
48 densely-connected nodes (hubs) in this network. It may also have block structure in such a wastewater
49 propagation network implying wastewater propagation chains. That's why we can find important APL
50 coefficients and grouped APL as Lu et al. (2013) and Chen et al. (2014) and analyze wastewater
51 propagation chains as Tu et al. (2017).

52 Using the sequential input-occupancy-output water resource tables of 49 sectors in China, we
53 calculate the average impact distance of wastewater discharge between sectors. At the same time, the
54 hub sectors and hub APLs of wastewater discharge in the economic system play significant roles in
55 analyzing and evaluating wastewater discharge in the entire economic system. However, there is
56 currently a lack of corresponding method for exploring the hub industries and hub APLs. In this paper,
57 we couple APL with hub covariance graph (Tan et al., 2014) (APL-HCG) to analyze and evaluate the
58 evolutionary process and wastewater transmission mechanisms of China. APL-HCG directly and
59 generally reveals the hubs of economy and block structures implying economic significance
60 intrinsically embedded in the APL matrix, i.e. significant propagation chains (production or
61 wastewater discharge or other economic meanings). Comparing with past researches, APL-HCG
62 considers marginally economic dependence representing by wastewater APL covariance between
63 sectors. It is a direct and general framework to better uncover intrinsically economic hub industries
64 and significant propagation chains (hub APLs) and to better reflect the linkage relevance by
65 considering possibly marginal dependence of all sectors. With hub sectors and hub wastewater
66 propagation chains, we can make strategies for wastewater discharge control or wastewater treatment.

67 The following contents of this article are arranged as follows: The second part introduces the data
68 and models used to analyze and evaluate hub sectors and hub propagation chains of wastewater

69 discharge; the third part illustrates the result and analysis of hub sectors and hub propagation chains;
 70 the fourth part carries on the article summarization and proposes corresponding policy implications.
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72 **2 Methodology**

73 **2.1 Data**

74 We compiled water resource input-occupancy-output tables of 49 sectors for year 2002, 2007,
 75 2012 and 2017 based on the input-output tables released by the National Bureau of Statistics and the
 76 statistical data announced by the Environmental Statistics Yearbook, Energy Statistics Yearbook and
 77 National Water Bulletin and so on. The occupancy includes 12 indicators: Water Consumption (100
 78 million cubic meters), Wastewater Discharge (100 million tons), Chemical Oxygen Demand (COD)
 79 (10,000 tons), Ammonia Nitrogen Emissions (NH) (10,000 tons), Coal Consumption (10,000 tons),
 80 Crude Oil Consumption (10,000 tons), Natural Gas Consumption (100 million cubic meters), and
 81 Total Primary Energy Consumption (10,000 tons of standard coal), Employed Population (10,000
 82 people), Capital Deposit (10,000 Chinese yuan), Sulfur Dioxide Emissions (SO₂) (10,000 tons) and
 83 Carbon Dioxide Emissions (CO₂) (10,000 tons). Due to the inability to obtain wastewater discharge
 84 data from the agricultural sectors, 5 agricultural sectors (Agricultural Products, Forest Products,
 85 Animal Husbandry Products, Fishery Products and Agriculture, Forestry, Animal Husbandry and
 86 Fishery Service Products) have all zero wastewater emissions in the compiled 49-industry water
 87 resource input-occupancy-output table. In addition, data on Chemical Oxygen Demand, Ammonia
 88 Nitrogen Emissions and Crude Oil Consumption for some sectors are not available, so they are vacant.
 89 See Appendix A for structure description of the tables and Appendix B for information about 49
 90 sectors.

91 **2.2 Model**

92 A hub penalty function is used to discover densely-connected or hub nodes in a graph (Tan et al.,
 93 2014). Namely,

$$P(\Theta) = \min_{V, Z: \Theta = Z + V + V^T} \left\{ \lambda_1 \|Z - \text{diag}(Z)\|_1 + \lambda_2 \|V - \text{diag}(V)\|_1 + \lambda_3 \sum_{j=1}^p \| (V - \text{diag}(V))_j \|_q \right\} \quad (1)$$

94 where Θ is parameter matrix, symmetric matrix Z is sparse whose non-zero elements stand for edges
 95 between nodes, V 's non-zero columns represent hub nodes.

96 For observations $X = \{x_i\}_{i=1}^n, x_i \in \mathbb{R}^p$, combining specific loss function $\ell(X, \Theta)$ with hub
 97 penalty function $P(\Theta)$ yields a general convex optimization problem of hub graphical model ,

$$\begin{aligned} & \min_{\Theta \in \mathcal{S}, V, Z} \left\{ \ell(X, \Theta) + \lambda_1 \|Z - \text{diag}(Z)\|_1 + \lambda_2 \|V - \text{diag}(V)\|_1 + \lambda_3 \sum_{j=1}^p \| (V - \text{diag}(V))_j \|_q \right\} \\ & \text{s. t. } \Theta = Z + V + V^T \end{aligned} \quad (2)$$

98 In this paper, we will take hub graphical model to be APL hub covariance graph which is
 99 formulated as:

$$\begin{aligned} \min_{\Sigma \in \mathcal{S}, V, Z} & \left\{ \frac{1}{2} \|\Sigma - S\|_F^2 + \lambda_1 \|Z - \text{diag}(Z)\|_1 + \lambda_2 \|V - \text{diag}(V)\|_1 + \lambda_3 \sum_{j=1}^p \left\| (V - \text{diag}(V))_j \right\|_q \right\} \\ \text{s. t. } & \Sigma = Z + V + V^T \end{aligned} \quad (3)$$

100 where S denotes empirical covariance matrix of APL.

101 Convex optimization problem (2) and its specific form (3) can be solved by ADMM algorithm as
 102 described in Tan et al. (2014). For more details about ADMM, see, e.g., Tan et al. (2014), Eckstein
 103 and Bertsekas (1992), Ma et al. (2013), Boyd et al. (2010) and Eckstein (2012). For more fine
 104 discussion about hub covariance graph, see, e.g., Tan et al. (2014), Xue et al. (2012), Drton and
 105 Richardson (2003), Chaudhuri et al. (2007), Drton and Richardson (2008).

106 Average propagation lengths (APL) (Dietzenbacher et al., 2005) imply average economy
 107 distance or the degree of economic relevance between sectors. They count average steps of effect that
 108 reflect the economic relevance is direct or indirect within sectors and how many steps one industry
 109 connects to others. Considering wastewater discharge, the APL means wastewater propagation
 110 lengths. Let

$$H = \hat{a}_w(I - A)^{-1}[(I - A)^{-1} - I] \quad (4)$$

$$Q = \hat{a}_w[(I - A)^{-1} - I] \quad (5)$$

112 where A is Leontief technical coefficient matrix, \hat{a}_w is diagonal matrix of wastewater discharge
 113 coefficients. And $V = (v_{ij})_{i,j=1}^s$ denote the Leontief's type of APL or backward APL, then

$$v_{ij} = \begin{cases} \frac{h_{ij}}{q_{ij}}, & \text{if } q_{ij} > 0 \\ 0, & \text{if } q_{ij} = 0 \end{cases} \quad (6)$$

115 From Ghosh's point of view, let B be Ghosh technical coefficient matrix, and

$$\tilde{H} = (I - B)^{-1}[(I - B)^{-1} - I]\hat{a}_w \quad (7)$$

$$\tilde{Q} = [(I - B)^{-1} - I]\hat{a}_w \quad (8)$$

117 Correspondingly, $\tilde{V} = (\tilde{v}_{ij})_{i,j=1}^s$ denote the Ghosh's type of APL or forward APL, then

$$\tilde{v}_{ij} = \begin{cases} \frac{\tilde{h}_{ij}}{\tilde{q}_{ij}}, & \text{if } \tilde{q}_{ij} > 0 \\ 0, & \text{if } \tilde{q}_{ij} = 0 \end{cases} \quad (9)$$

119 Theoretically, backward wastewater propagation lengths (pulling by final demand) equal forward
 120 wastewater propagation lengths (driving by cost). We can construct wastewater propagation networks
 121 using either of them.

123 3 Results

124 3.1 Wastewater Discharge Propagation Chains

When the elements of wastewater discharge intensity matrix $\mathbf{F} = (\mathbf{Q} + \tilde{\mathbf{Q}})/2$ less than a specific threshold T , we remove the corresponding wastewater discharge APL linkage. Figure 1-Figure 4 show the evolutionary process of wastewater propagation networks with wastewater discharge APL direct linkage in size in cost driving aspect from 2002 to 2017. Both in 2002 and 2017, only one wastewater discharge propagation chain that APL direct linkage in size found. Wastewater discharge amount (percentage of total wastewater discharge) of Chain.1 are 118.54(26.97%) and 119.10(17.02%), measured in 100 million cubic meters. In 2007 and 2012, there are three wastewater propagation chains respectively. Wastewater discharge amount (percentage of total wastewater discharge) of Chain.1 are 112.40(20.19%) and 104.10(15.20%), measured in 100 million cubic meters (Table 1). The results of Chain.1 illustrated the evolutionary wastewater transmission mechanisms. We claim sector with large sum of in degree and out degree as center. Therefore, a center can be categorized as cost driven center in the aspect that it produces much more wastewater driven by other sectors than the wastewater it drives other sectors or cost driving center in the opposite direction. In 2002, S27 (Metal Products, Machinery and Equipment Repair Services), S28 (Electricity, Steam and Hot Water Production and Supply (Excluding Water and Electricity)), S30 (Construction) and S33 (Business) are cost driven centers by other sectors. S14 (Papermaking, Printing and Cultural, Educational and Sporting Goods), S15 (Petroleum, Coking Products and Nuclear Fuel Processed Products) and S45 (Hydropower) are centers to drive other sectors (cost driving centers). In 2007, S27 (Metal Products, Machinery and Equipment Repair Services) and S45 (Hydropower) are cost driven centers. In 2012, S45 (Hydropower) and S46 (Water Supply) are cost driven centers. In year 2017, S31 (Merchandise Transportation and Storage (Excluding Water Transportation)), S33 (Business), S45 (Hydropower) and S46 (Water Supply) are cost driven centers, S14 (Papermaking, Printing and Cultural, Educational and Sporting Goods) are cost driving centers. Although some sectors are regarded as cost driven centers, they still have dense connections in the opposite direction (cost driving). For example, sectors S27 (Metal Products, Machinery and Equipment Repair Services) and S28 (Electricity, Steam and Hot Water Production and Supply (Excluding Water and Electricity)) in 2002; sectors S27 (Metal Products, Machinery and Equipment Repair Services) and S45 (Hydropower) in 2007; sectors S45 (Hydropower) and S46 (Water Supply) in 2012 and 2017. In a certain sense, there is ambiguity by adopting this heuristic rule because we may reach opposite results in the maximal degree aspect.

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Wastewater propagation chains (2002)

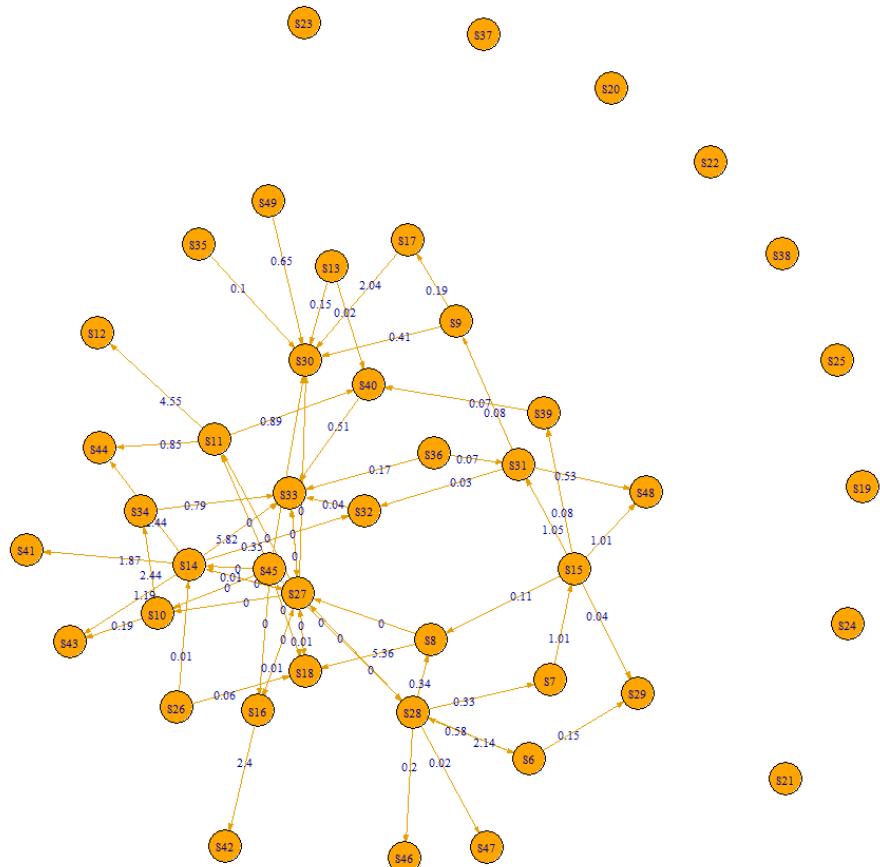


Figure 1: Wastewater propagation network with wastewater discharge APL direct linkage in size in cost driving aspect of 2002.

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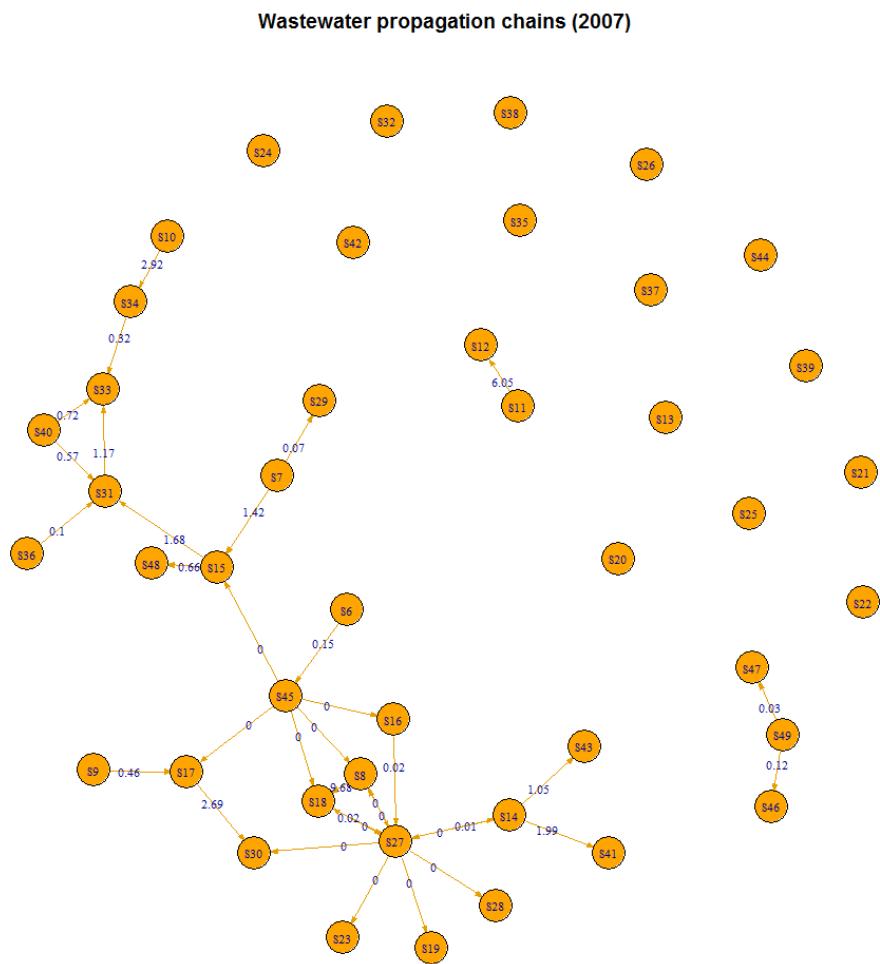
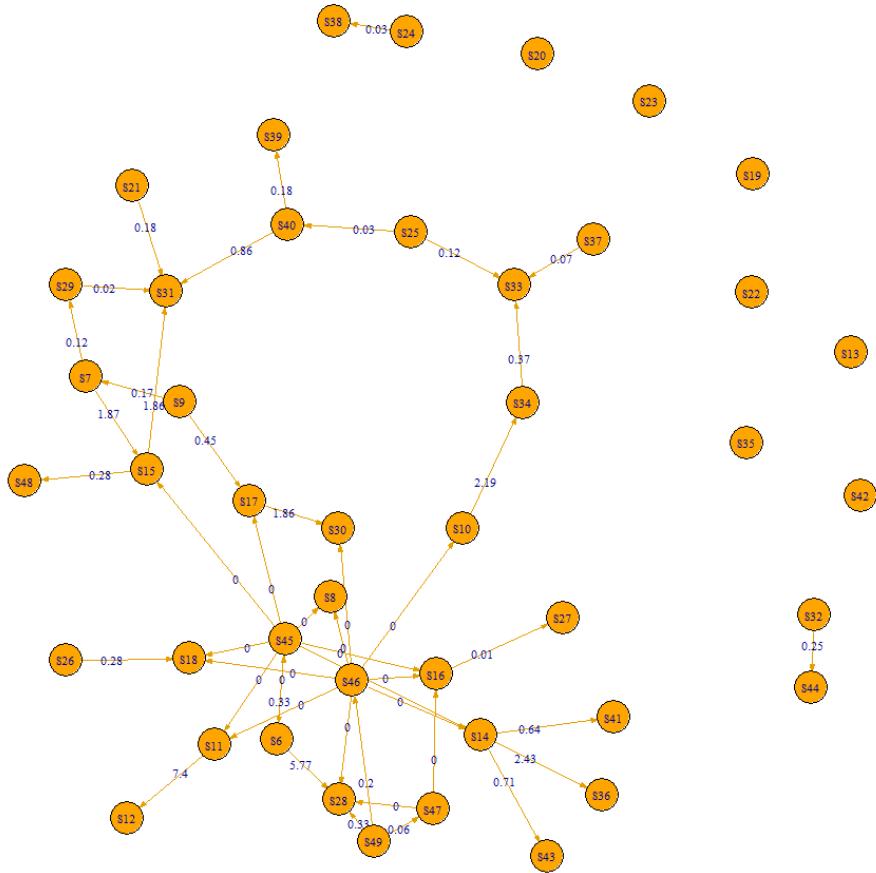


Figure 2: Wastewater propagation network with wastewater discharge APL direct linkage in size in cost driving aspect of 2007.

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Wastewater propagation chains (2012)



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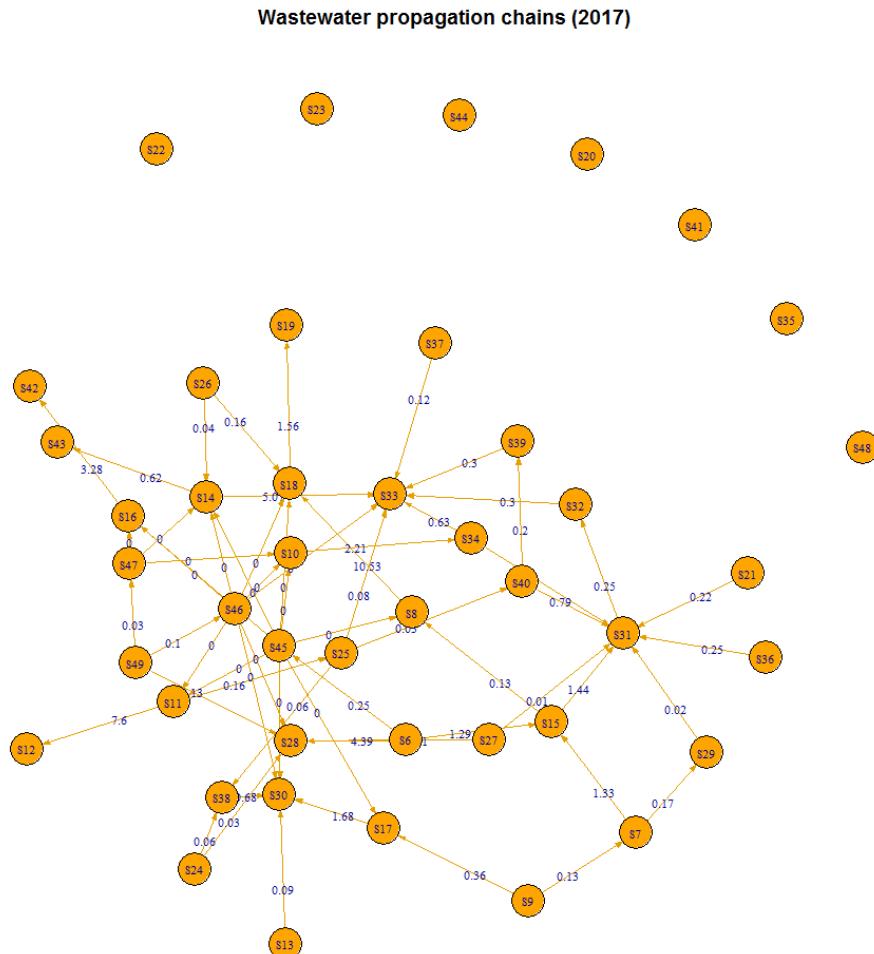


Figure 4: Wastewater propagation network with wastewater discharge APL direct linkage in size in cost driving aspect of 2017.

Table 1: Wastewater discharge amount (percentage of total wastewater discharge in bracket) of wastewater discharge propagation chains with wastewater discharge APL direct linkage in size of year 2002, 2007, 2012 and 2017, measured in 100 million cubic meters.

Year	Chain.1	Chain.2	Chain.3
2002	118.54(26.97%)	-	-
2007	112.40(20.19%)	6.05(1.09%)	0.15(0.03%)
2012	104.10(15.20%)	0.25(0.04%)	0.03(0.00%)
2017	119.10(17.02%)	-	-

3.2 Hub Wastewater Discharge Sectors

Some cost driven centers still have dense connections in the direction of cost driving, it implies

that we should take more broadly marginal dependence linkage into consideration when analyzing

center sectors in wastewater discharge APL network other than in single cost driven or cost driving direction. There are 44 sectors except for 5 agricultural sectors can be used to analyze potential key wastewater discharge hubs. We find some sectors are densely-connected to other sectors in the wastewater discharge average propagation lengths aspect. They might be hubs to control wastewater discharge or to treat wastewater in the whole economy system. In year 2002, there are 7 sectors are anchored to be potential hubs: Textile, Business, Information Transmission, Computer Services and Software, Scientific Research and Technical Services, Environment and Public Facilities Management, Health and Social Work, Water Supply (Figure 5(Hub industries (2002) and Table 2). Among them, Textile is a well-known labor-intensive and key heavy pollution industry according to “the First National Pollution Source Survey Program” issued at May, 2007. It discharged 2.1634 billion cubic meter wastewater in 2002. The statistics released by the National Environmental Protection Agency of China shows, total wastewater discharge from printing and dyeing industry ranks the 5th among all national manufacturing sectors and counting about 60% of total wastewater discharged by different sectors. Moreover, treating Textile-type wastewater is difficult, and the recycling rate is low. From the economic view, the Textile industry highly depended on external economies. China is the world's largest producer and exporter of textile clothing. It is essential to ensure the foreign exchange deposit, the balance of international payments, the stability of exchange rate of Chinese yuan, social employment and sustainable development of the Textile industry of China by keeping continuous and stable growth of textile clothing exports. The results of our method coordinate with reality and reflect the intensive-dependence of Textile industry to other sectors in the wastewater discharge APL aspect under the whole macroeconomic system. The rest of hub sectors all belong to the tertiary industry. It implies tertiary industry is responsible for most of the wastewater discharge connections in economy. For example, varieties of sectors inevitably directly or indirectly linked to Business that discharged 1.4866 billion cubic meter wastewater. High-tech industry Information Transmission, Computer Services and Software discharged 0.4164 billion cubic meter wastewater taking about 1% of total wastewater discharge in the economy. Scientific Research and Technical Services, Environmental Resources and Public Facilities Management, Health and Social Work and Water Supply altogether released about 0.85% of total wastewater. However, they are densely-connected to other sectors in the relationship of wastewater discharge. One of the explanations to this phenomenon might be the products the former three sectors used implicitly embedding wastewater discharge. And Water Supply industry densely-connected to other sectors is ordinary due to the fact that water possesses vital importance for all sectors.

213 In year 2007, only 3 sectors are hubs. They are Merchandise Transportation and Storage
214 (Excluding Water Transportation), Environment and Public Facilities Management, Education
215 respectively (Figure 5(Hub industries (2007) and Table 2).

216 In year 2012, ten sectors are found to be hubs: Food Manufacturing and Tobacco, Textile, Wood
217 Processing and Furniture, Catering, Real Estate, Environment and Public Facilities Management,
218 Health and Social Work, Water Supply, Sewage Treatment, Water Management (Figure 5(Hub
219 industries (2012) and Table 2). The wastewater discharge of sectors Food Manufacturing and Tobacco
220 and Textile ranked the fourth and the fifth respectively. Other hub sectors take about 2.20%
221 responsibility of total wastewater discharge of the whole nation. Environment and Public Facilities
222 Management, Health and Social Work and Water Supply are the same with year 2002. Sewage
223 Treatment becomes hub industry for the first time which reflects that more and more attention is paid
224 to the safety of water environment, sustainable development of water resource and forward
225 environmental protection related to water.

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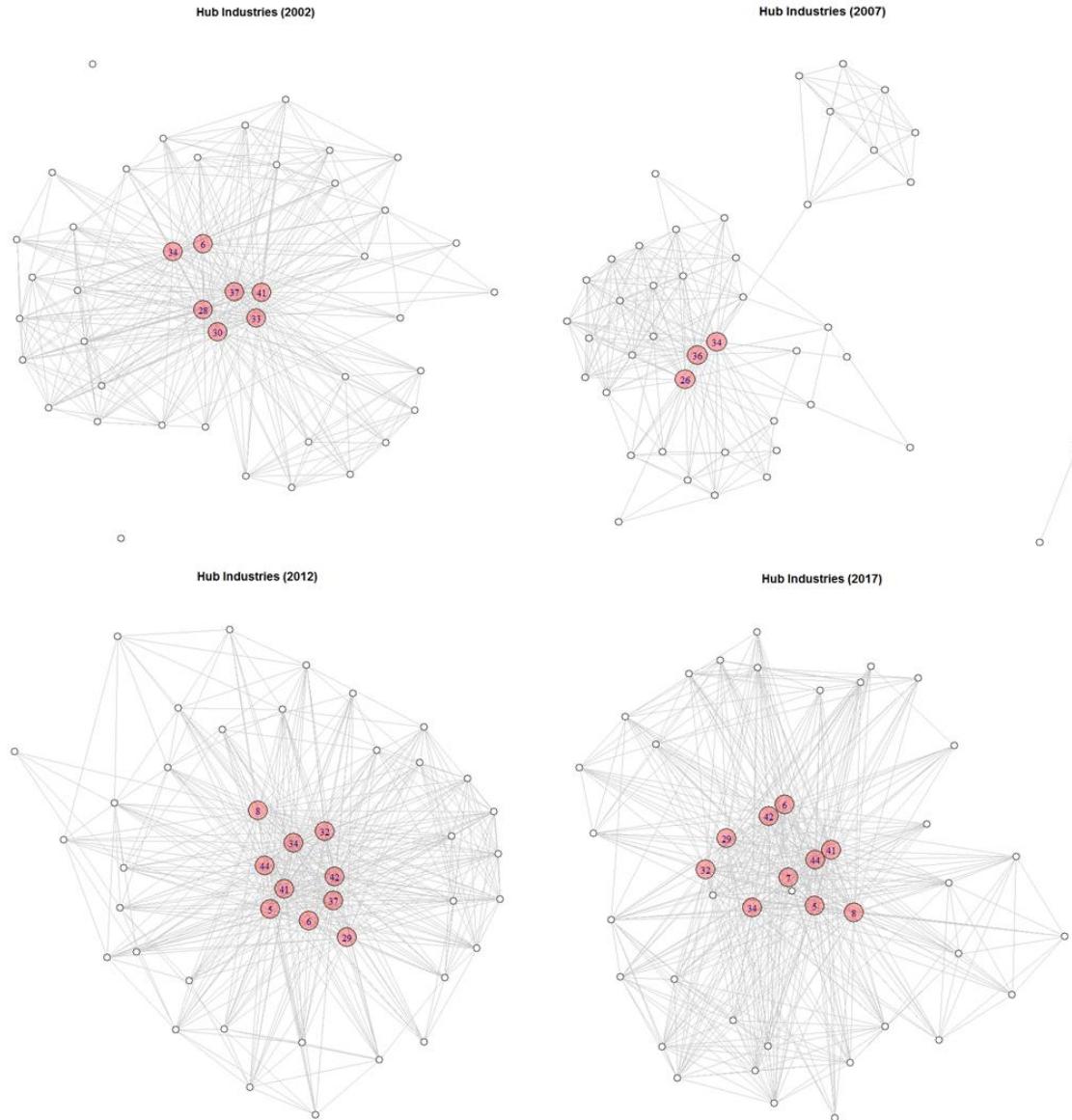


Figure 5: Hub wastewater discharge sectors of 2002, 2007, 2012 and 2017 under hub wastewater discharge APL covariance graphical model.

Table 2: The number of edges representing by the elements of Sigma and Z. The hub wastewater discharge sectors and the number of edges within each hub sector. The last column is the number of edges in size (directly or indirectly) shown in Appendix E.

Year	Number.of. Edges (Sigma)	Number.of. Edges (Z)	Hub.Sectors	Number.of.Ed ges (Hub)	Number.of.Edges.in .Size (Hub)
2002	358	201	S11, S33, S35, S38, S39, S42, S46	33, 38, 37, 38, 31, 40, 41	12, 17, 4, 0, 3, 1, 4
2007	235	197	S31, S39, S41	29, 30, 30	6, 0, 0
2012	453	202	S10, S11, S13, S34,	40, 37, 39, 35,	6, 6, 2, 4, 1, 1, 1, 5,

			S37, S39, S42, S46,	37, 39, 39, 40,	2, 2
			S47, S49	39, 41	
2017	456	191	S10, S11, S12, S13,	42, 37, 39, 39,	5, 6, 2, 3, 4, 1, 2, 3,
			S34, S37, S39, S46,	34, 35, 38, 40,	1, 2
			S47, S49	39, 41	

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235 For year 2017, Food Manufacturing and Tobacco, Textile, Textile Clothing, Shoes, Hats, Leather,
 236 Down and Their Products, Wood Processing and Furniture, Catering, Real Estate, Environment and
 237 Public Facilities Management, Water Supply, Sewage Treatment, Water Management (Figure 5(Hub
 238 industries (2017) and Table 2). It is almost the same as year 2012 except for industry Textile Clothing,
 239 Shoes, Hats, Leather, Down and Their Products that is not a hub in year 2012. And industry Health
 240 and Social Work is no longer a hub in year 2017. The analysis for specific sectors may refer to the
 241 conclusion summarized for year 2002, 2007 and 2012. The dynamics course of the evolution of hub
 242 sectors from year 2002 to 2017 shows: (1) Regular distribution pattern of hub sectors under
 243 wastewater APL framework remains consistent in year 2002, 2012 and 2017. One side of the hubs
 244 belongs to the top highly discharge wastewater sectors but important to meet people's daily food,
 245 clothing, housing and transportation needs, the other side of hubs belongs to lightly water polluting
 246 sectors like high-tech sectors and public service sectors. (2) It illustrates water protection and
 247 sustainable development of water resource has attracted much more attention as Sewage Treatment
 248 industry became a key hub since year 2012. (3) For wastewater discharge control or wastewater
 249 treatment, the governance can be taken with both hands. On the one hand, government may consider
 250 taking strict and efficient policies and measures to control wastewater discharge of highly water
 251 polluting sectors. On the other hand, the government can advocate lightly water polluting hub sectors
 252 to raise environmental protection requirements for products they used.

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254 **3.3 Hub Wastewater Propagation Chains**

255 Substituting non-zero elements of symmetric sparse matrix \mathbf{Z} with wastewater APL, we can
 256 recover the adjacency matrix of sectors. Wastewater propagation networks with hub are showed in
 257 Figure 6-Figure9. The hub sectors in the networks can be regarded as grips to wastewater treatment.
 258 So an ideal propagation chain to wastewater treatment may contain hub sectors and can reflect the
 259 most significant linkages. By analyzing the hub wastewater propagation networks, it illustrates the
 260 most explanatory transmission course of wastewater discharge. We carefully select the wastewater
 261 propagation chains according to the following rules: containing as much hub sectors as possible;
 262 coordinate with reality logic of economy. The results are presented in Figure 6-Figure 9 and Table 3.

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Hub wastewater propagation chains (2002)

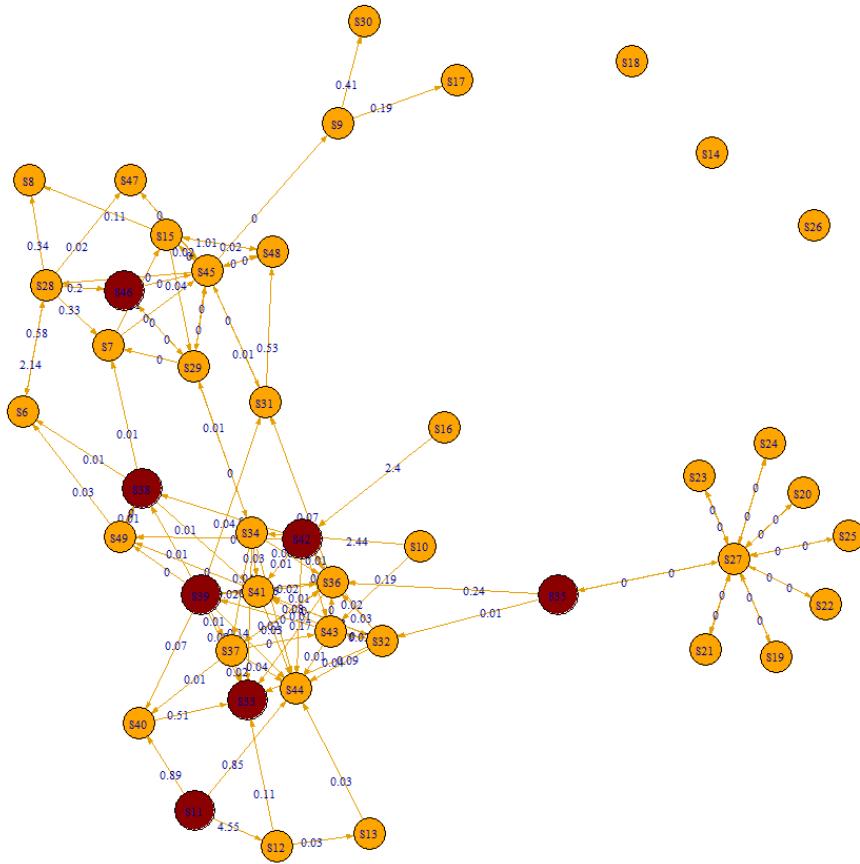


Figure 6: Hub wastewater propagation network with wastewater discharge APL direct linkage in size in cost driving aspect under hub wastewater discharge APL covariance graphical model of 2002.

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Hub wastewater propagation chains (2007)

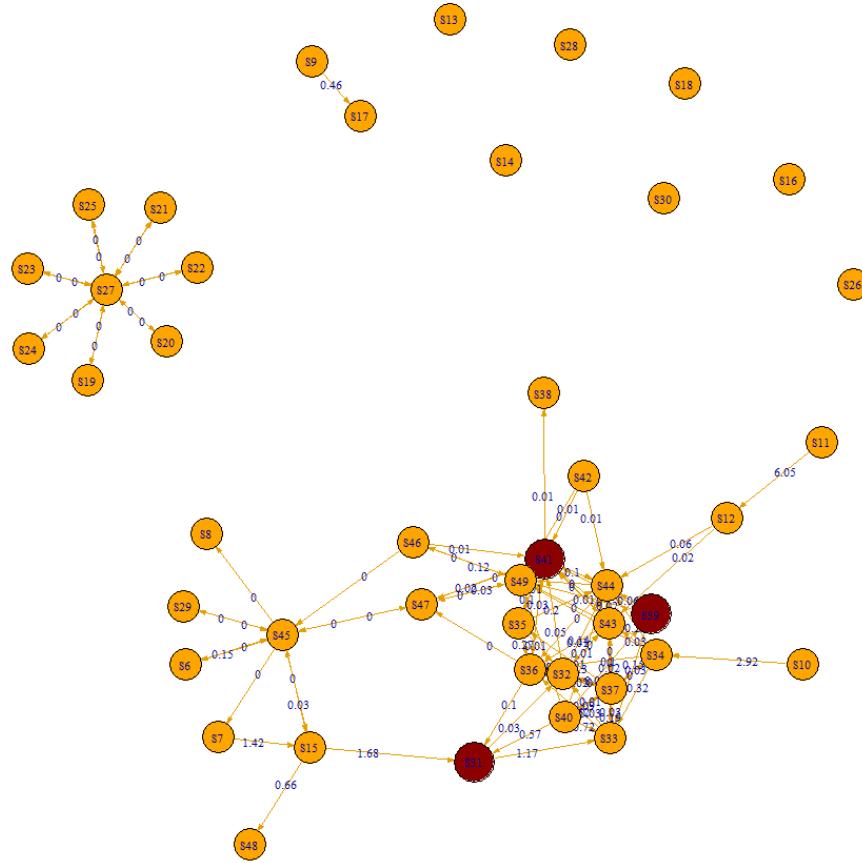


Figure 7: Hub wastewater propagation network with wastewater discharge APL direct linkage in size in cost driving aspect under hub wastewater discharge APL covariance graphical model of 2007.

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Hub wastewater propagation chains (2012)

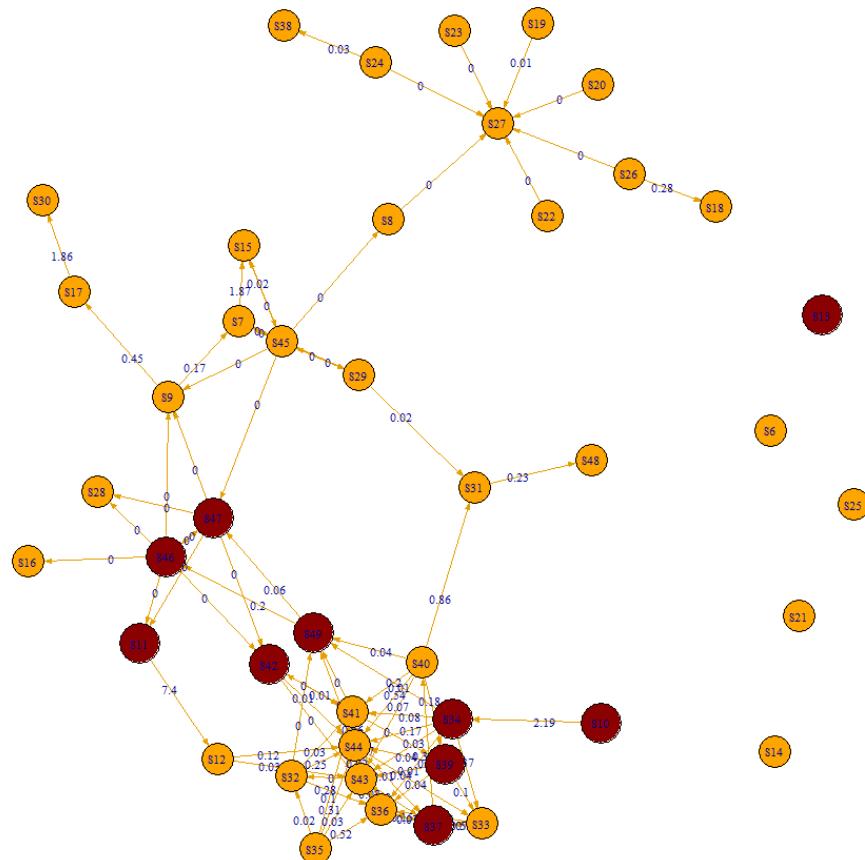


Figure 8: Hub wastewater propagation network with wastewater discharge APL direct linkage in size in cost driving aspect under hub wastewater discharge APL covariance graphical model of 2012.

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Hub wastewater propagation chains (2017)

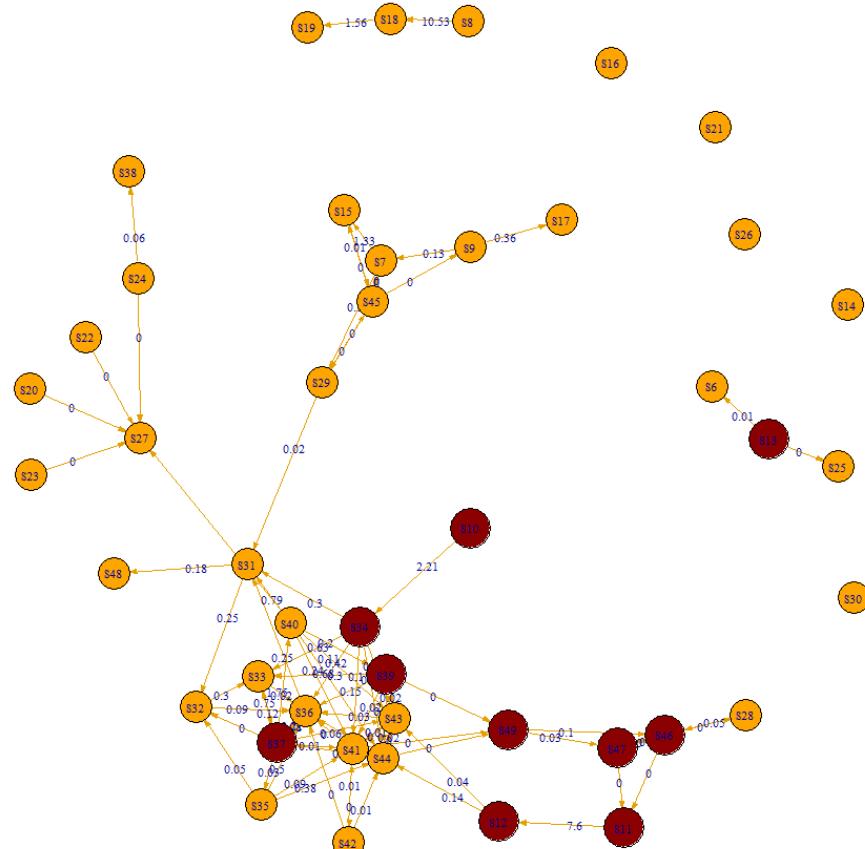


Figure 9: Hub wastewater propagation network with wastewater discharge APL direct linkage in size in cost driving aspect under hub wastewater discharge APL covariance graphical model of 2017.

Table 3: Wastewater discharge amount of hub wastewater discharge propagation chains with wastewater discharge APL direct linkage in 2002, 2007, 2012 and 2017, measured in 100 million cubic meters

Year	Hub.Chain.1	Hub.Chain.2	Hub.Chain.3
2002	39.84(9.06%)	-	-
2007	43.38(7.79%)	0.46(0.08%)	0.00(0.00%)
2012	64.55(9.43%)	-	-
2017	40.91(5.85%)	12.09(1.73%)	0.01()

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In 2002, 2007, 2012 and 2017, Hub.Chain.1 directly illustrated by APL-HCG accounts for 9.06%, 9%, 9.43% and 5.85% of total wastewater discharge, namely 39.84, 43.38, 64.55 and 40.91 100 million cubic meters. In 2012, hub sector S13 (Wood Processing and Furniture) is eliminated from direct linkage propagation chains. By considering more broadly marginal dependence linkages when

286 analyzing center sectors in wastewater discharge APL network other than in single cost driven or cost
287 driving direction, we erase the ambiguity of centers in wastewater APL network only keeping direct
288 linkage in size. For example, S27 (Metal Products, Machinery and Equipment Repair Services) and
289 S45 (Hydropower) which have opposite meanings in different heuristics are never again been center
290 sectors in direct linkage in size APL-HCG (Figure 6-Figure 9). The wastewater discharge of marginal
291 dependence edges embracing around S27 and S45 holds very small. The ambiguous center sector S46
292 (Water Supply) in the wastewater propagation network with wastewater discharge APL direct linkage
293 in size still a hub in the hub wastewater propagation network. Surrounding water supply and
294 wastewater treatment, we can illuminate hub transmission chains. In 2002, they are S6(Coal Mining
295 and Washing Products)<->S28(Electricity, Steam and Hot Water Production and Supply (Excluding
296 Water and Electricity))->S46(Water Supply)->S45(Hydropower)<->S47(Sewage Treatment) and
297 S10(Food Manufacturing and Tobacco Processing)->S34(Catering)<->S29(Gas Production and
298 Supply)<->S46(Water Supply)->S45(Hydropower) <->S47(Sewage Treatment). In 2007, it is S7(Oil
299 and Gas Extraction Products)->S15(Petroleum, Coking Products and Nuclear Fuel Processed
300 Products)<->S45(Hydropower)<->S47(Sewage Treatment)<->S49(Water Management)<-
301 >S46(Water Supply)->S41(Education)<->S47(Sewage Treatment). In 2012, it is S10(Food
302 Manufacturing and Tobacco Processing)->S34(Catering)->S49(Water Management)->S46(Water
303 Supply)<->S47(Sewage Treatment). In 2017, they are S11(Textile)->S12(Textile Clothing, Shoes,
304 Hats, Leather, Down and Their Products)->S44(Public Administration, Social Security and Social
305 Organization)->S49(Water Management)->S46(Water Supply)<->S47(Sewage Treatment) and
306 S10(Food Manufacturing and Tobacco Processing)->S34(Catering)->S44(Public Administration,
307 Social Security and Social Organization)->S49(Water Management)->S46(Water Supply)<-
308 >S47(Sewage Treatment). Therefore, the transmission mechanisms about water supply and
309 wastewater treatment evolve from heavy industry sources like Coal Mining and Washing Products,
310 Oil and Gas Extraction Products to light industry source like Textile. However, transmission
311 mechanism originating from Food Manufacturing and Tobacco Processing->Catering always play
312 significant role in water supply and wastewater treatment. In addition, densely-connected block
313 structures including sectors Water Supply, Sewage Treatment and Water Management are found in
314 hub wastewater propagation network with wastewater discharge APL direct linkage in size, as shown
315 by Figure 6-Figure 9 and Appendix F. Hub transmission chains and hub block structures all may reflect
316 the evolutionary and most significant transmission mechanisms in a more broadly marginal
317 dependence linkages aspect.

318 Hub.Chain.1 that lies in linkage in size wastewater propagation network is responsible for 5.03%,
319 1.97%, 1.12% and 1.73% of total wastewater discharge, absolutely 22.12, 10.98, 7.66 and 12.09

320 measured in 100 million cubic meters respectively (Appendix C and Appendix D). It makes sense to
321 construct explanatory transmission mechanism in a maximal wastewater discharge aspect. However,
322 in 2017, Hub.Chain.1 is S8(Metal Mining Products)->S18(Metal Smelting and Calendered Products)-
323 >S19(Metal Products). It plots the industrial upstream and downstream wastewater driving chain
324 relationship of metal industry coordinate with reality. But the Hub.Chain.1 of 2017 excludes hub
325 sectors. Hub.Chain.1 of 2002, 2007 and 2012 contain 4, 1 and 4 hub sectors respectively and they are
326 the chains including the most hub sectors in corresponding years.

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328 **4 Conclusions and Implications**

329 This paper calculates the average propagation lengths of wastewater discharge between sectors
330 through the compilation of sequential water input-occupancy-output tables for 2002, 2007, 2012 and
331 2017. In view of current deficiency of ambiguity in analytic results of economic hubs and
332 transmission mechanisms, we propose to introduce more broadly marginal dependence linkages. A
333 coupled model named APL-HCG (APL with hub covariance graph) is proposed to analyze the hub
334 wastewater discharge sectors and hub propagation chains in overall economic system. The basic
335 conclusion is as follows: (1) We distinguish cost driven center sectors and cost driving center sectors
336 in a general wastewater propagation network with wastewater discharge APL direct linkage in size.
337 Metal Products, Machinery and Equipment Repair Services and Hydropower are two common seen
338 cost driven centers, Papermaking, Printing and Cultural, Educational and Sporting Goods is a
339 common seen cost driving center. (2) Regular distribution pattern of hub sectors under wastewater
340 APL framework remains consistent in year 2002, 2012 and 2017. One side of the hubs belongs to the
341 top highly discharge wastewater sectors but important to meet people's daily food, clothing, housing
342 and transportation needs, the other side of hubs belongs to lightly water polluting sectors like high-
343 tech sectors and public service sectors. (3) It illustrates water protection and sustainable development
344 of water resource has attracted much more attention as Sewage Treatment industry became a key hub
345 since year 2012. (4) For wastewater discharge control or wastewater treatment, the governance can
346 implement with both hands. On the one hand, government may consider taking strict and efficient
347 policies and measures to control wastewater discharge of highly water polluting sectors. On the other
348 hand, the government can advocate lightly water polluting hub sectors to raise environmental
349 protection requirements for products they used. (5) Textile shows the maximum effectiveness in
350 wastewater reduction. The most important wastewater propagation chains imply that hub sectors like
351 Textile should be considered as one of the best grips in wastewater treatment. (6) The transmission
352 mechanisms about water supply and wastewater treatment evolve from heavy industry sources like
353 Coal Mining and Washing Products, Oil and Gas Extraction Products to light industry source like

354 Texitile. (7) Transmission mechanism originating from Food Manufacturing and Tobacco Processing-
355 >Catering always play significant role in water supply and wastewater treatment. (8) Densely-
356 connected block structures including sectors Water Supply, Sewage Treatment and Water
357 Management are found in hub wastewater propagation network with wastewater discharge APL direct
358 linkage in size. In a word, with the illumination of propagation chains in general wastewater
359 propagation networks, hub sectors, hub transmission chains and hub block structures in hub
360 wastewater propagation networks, it may reflect the evolutionary and most significant transmission
361 mechanisms in a more broadly marginal dependence linkages aspect.

362

363 **ACKNOWLEDGEMENTS**

364 I gratefully thank Professor Xiuli Liu, Ph.D Xin Xiang and Ph.D Minghui Qin for comments on the
365 methodology and earlier draft of this manuscript.

366

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414 **Appendix A. Water Resource Input-Occupancy-Output Table Format for**
 415 **Year 2002, 2007, 2012 and 2017**

Input		Output		
		Intermediate Demand	Final Demand	Total Output
		Z	f	X
Occupancy	Intermediate Input	Z	f	X
	Value-added	V		
	Total Input	X		
	Water Consumption	W _I	W _f	W
	Wastewater Discharge	WD _I	WD _f	WD
	Chemical Oxygen Demand	COD _I	COD _f	COD
	Ammonia Nitrogen Emissions	NH _I	NH _f	NH
	Coal Consumption	C _I	C _f	C
	Crude Oil Consumption	CO _I	CO _f	CO
	Natural Gas Consumption	NG _I	NG _f	NG
	Total Primary Energy Consumption	TPE _I	TPE _f	TPE
	Employed Population	EP _I		EP
	Capital Deposit	CD _I		CD
	Sulfur Dioxide Emissions	SO _{2I}	SO _{2f}	SO ₂
	Carbon Dioxide Emissions	CO _{2I}		CO ₂

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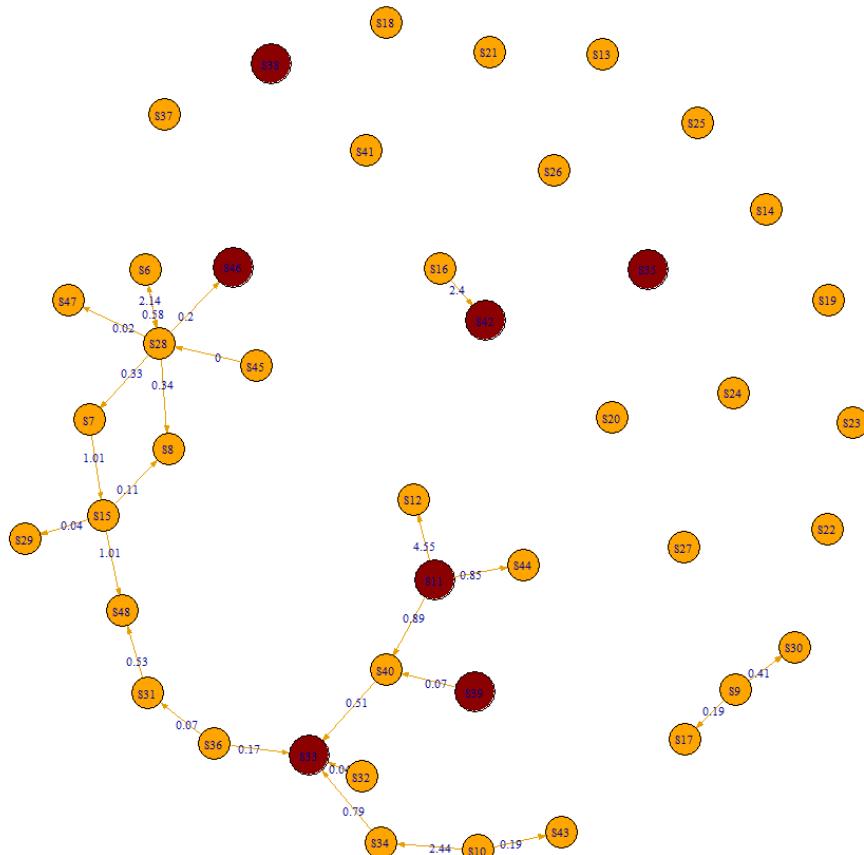
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419**Appendix B. Sector Code**

Code	Sector	Code	Industry
S1	Agricultural Products	S26	Waste Resources and Waste Material Recycling Processed Products
S2	Forest Products	S27	Metal Products, Machinery and Equipment Repair Services
S3	Animal Husbandry Products	S28	Electricity, Steam and Hot Water Production and Supply (Excluding Water and Electricity)
S4	Fishery Products	S29	Gas Production and Supply
S5	Agriculture, Forestry, Animal Husbandry and Fishery Service Products	S30	Construction
S6	Coal Mining and Washing Products	S31	Merchandise Transportation and Storage (Excluding Water Transportation)
S7	Oil and Gas Extraction Products	S32	Postal Service
S8	Metal Mining Products	S33	Business
S9	Non-metallic Mining Products	S34	Catering
S10	Food Manufacturing and Tobacco Processing	S35	Information Transmission, Computer Services and Software
S11	Textile	S36	Finance and Insurance
S12	Textile Clothing, Shoes, Hats, Leather, Down and Their Products	S37	Real Estate
S13	Wood Processing and Furniture	S38	Scientific Research and Technical Services
S14	Papermaking, Printing and Cultural, Educational and Sporting Goods	S39	Environment and Public Facilities Management
S15	Petroleum, Coking Products and Nuclear Fuel Processed Products	S40	Resident Services, Repairs and Other Services
S16	Chemical Products	S41	Education
S17	Non-metallic Mineral Products	S42	Health and Social Work
S18	Metal Smelting and Calendered Products	S43	Culture, Sports and Entertainment
S19	Metal Products	S44	Public Administration, Social Security and Social Organization
S20	Mechanical Equipment	S45	Hydropower
S21	Transportation Equipment	S46	Water Supply
S22	Electrical Machinery and Equipment	S47	Sewage Treatment
S23	Communication Equipment, Computers and Other Electronic Equipment	S48	Water Transportation
S24	Instrumentation	S49	Water Management
S25	Other Manufactured Products		

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423 Appendix C. Hub wastewater propagation chains with wastewater API
424 direct linkage in size and labeled each linkage with direct wastewater
425 discharge amount in cost driving aspect (denoted by out arrows).

Hub wastewater propagation chains (2002)

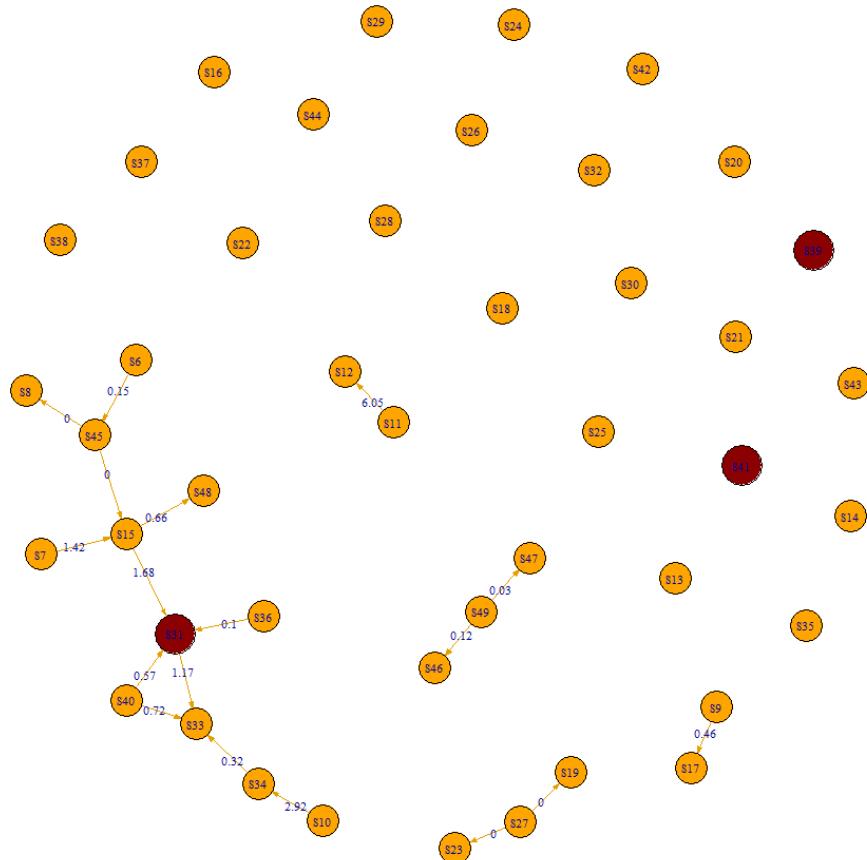


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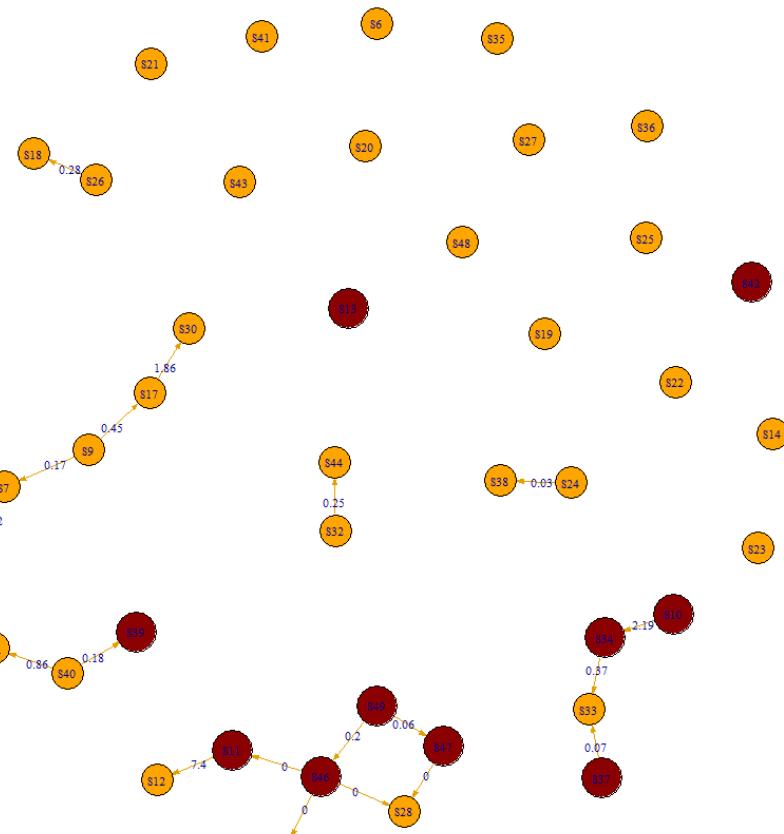
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Hub wastewater propagation chains (2007)



Hub wastewater propagation chains (2012)



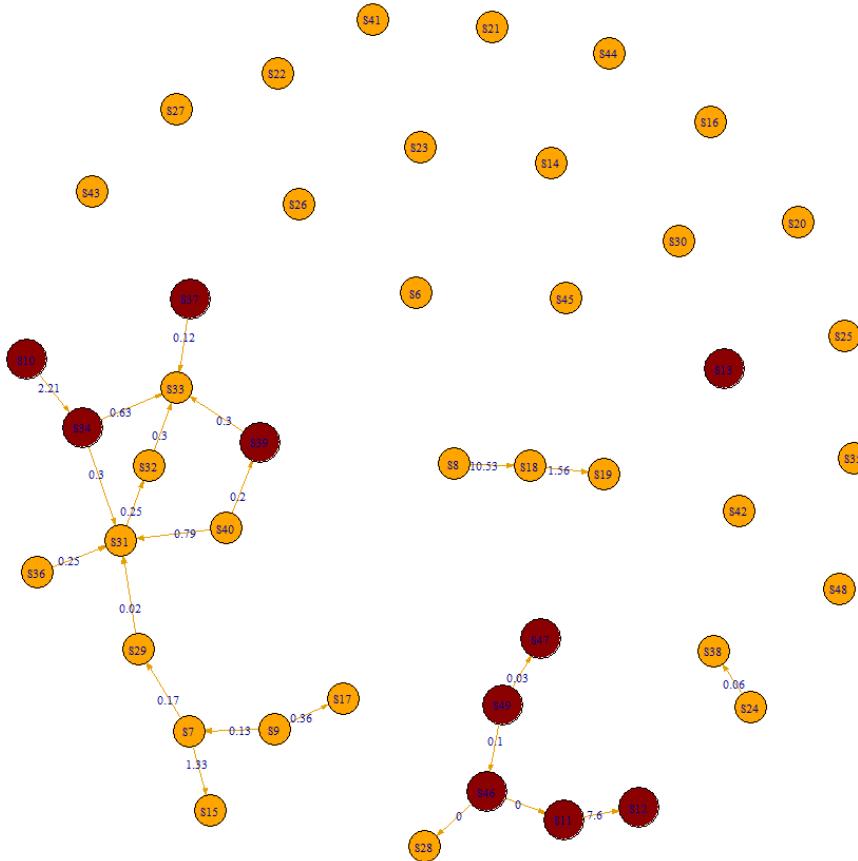
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Hub wastewater propagation chains (2017)



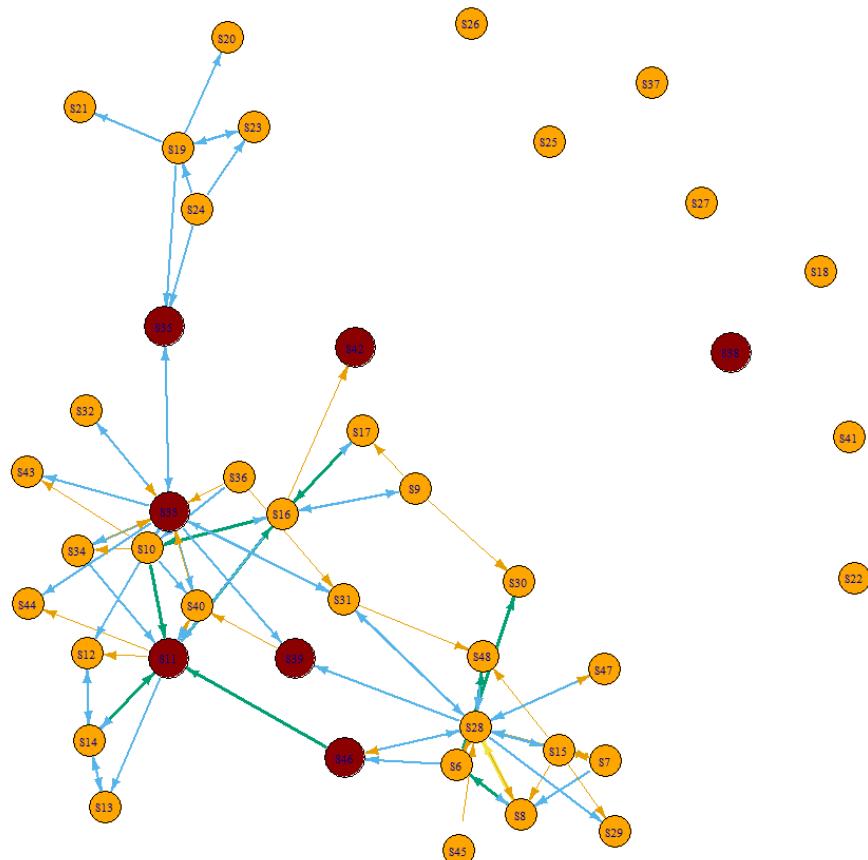
Appendix D. Wastewater discharge amount of hub wastewater discharge propagation chains with wastewater discharge APL direct linkage in size in 2002, 2007, 2012 and 2017, measured in 100 million cubic meters.

Year	Hub.Chain.1	Hub.Chain.2	Hub.Chain.3	Hub.Chain.4	Hub.Chain.5	Hub.Chain.6
2002	22.12(5.03%)	2.40(0.55%)	0.60(0.14%)	-	-	-
2007	10.98(1.97%)	6.05(1.09%)	0.46(0.08%)	0.15(0.03%)	0.00(0.00%)	-
2012	7.66(1.12%)	5.53(0.81%)	2.63(0.38%)	0.28(0.04%)	0.25(0.04%)	0.03(0.00%)
2017	12.09(1.73%)	7.73(1.10%)	7.36(1.05%)	0.06(0.01%)	-	-

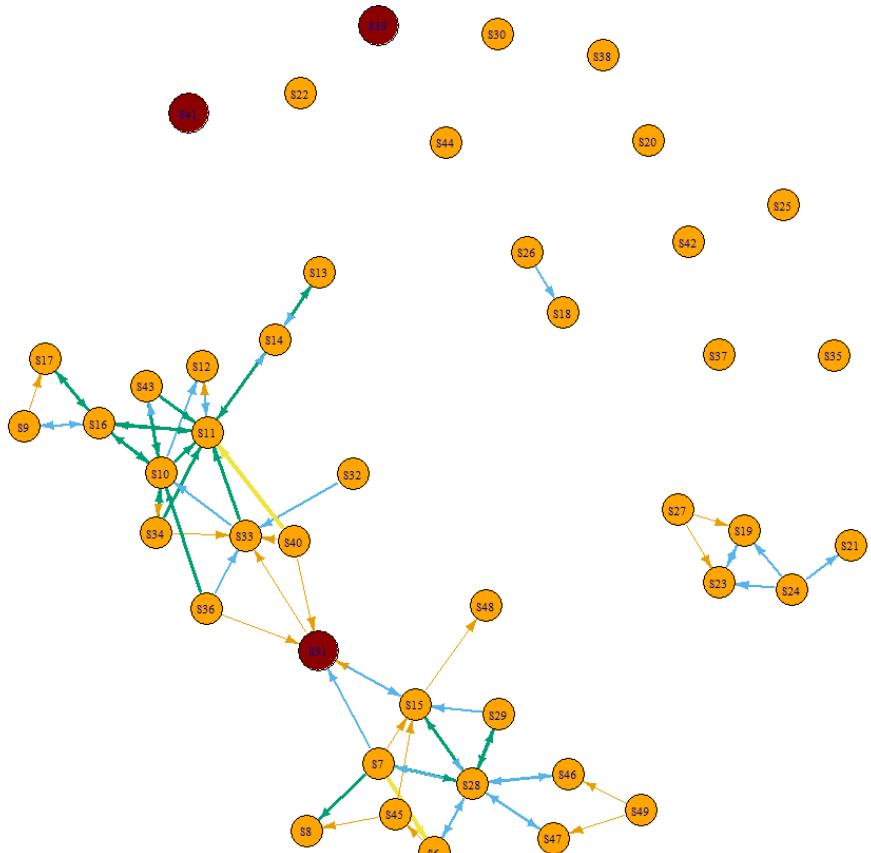
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Appendix E. Hub wastewater propagation chains with wastewater APL linkage in size.

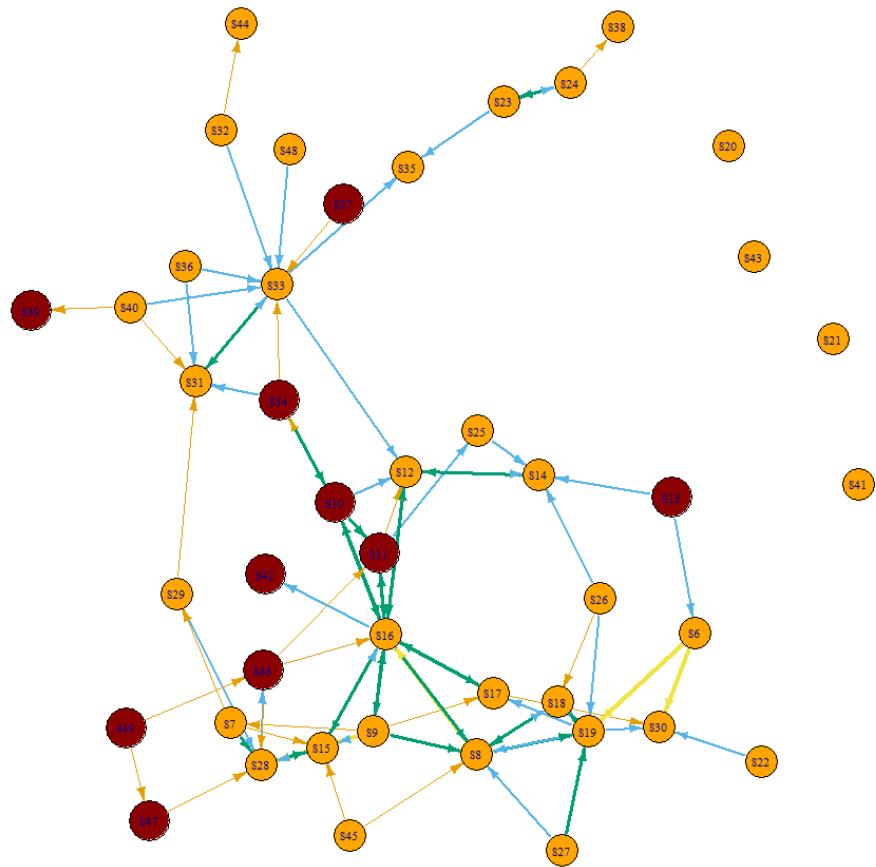
Hub wastewater propagation chains (2002)



Hub wastewater propagation chains (2007)

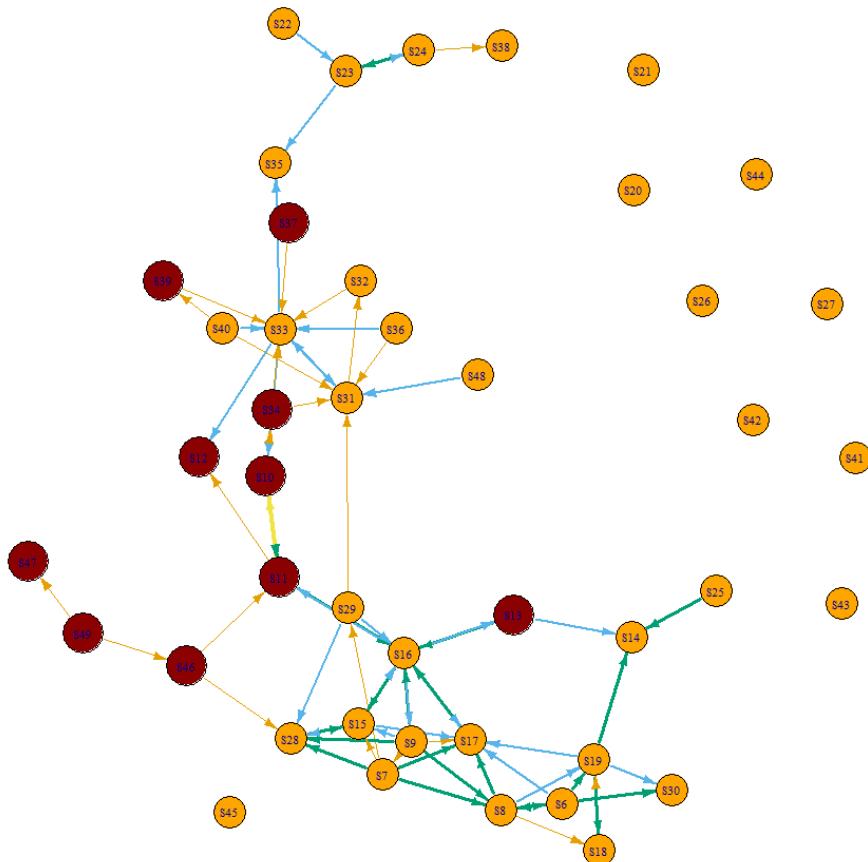


Hub wastewater propagation chains (2012)

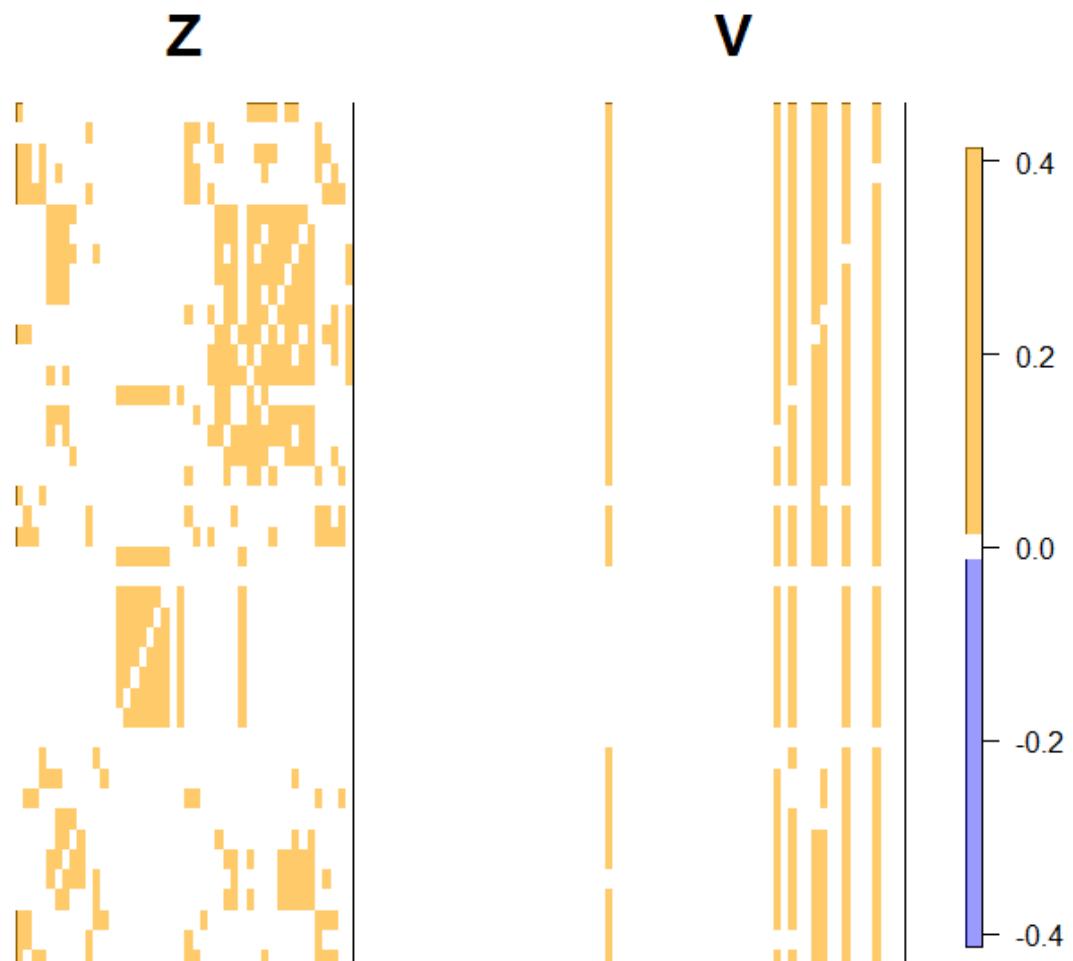


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Hub wastewater propagation chains (2017)

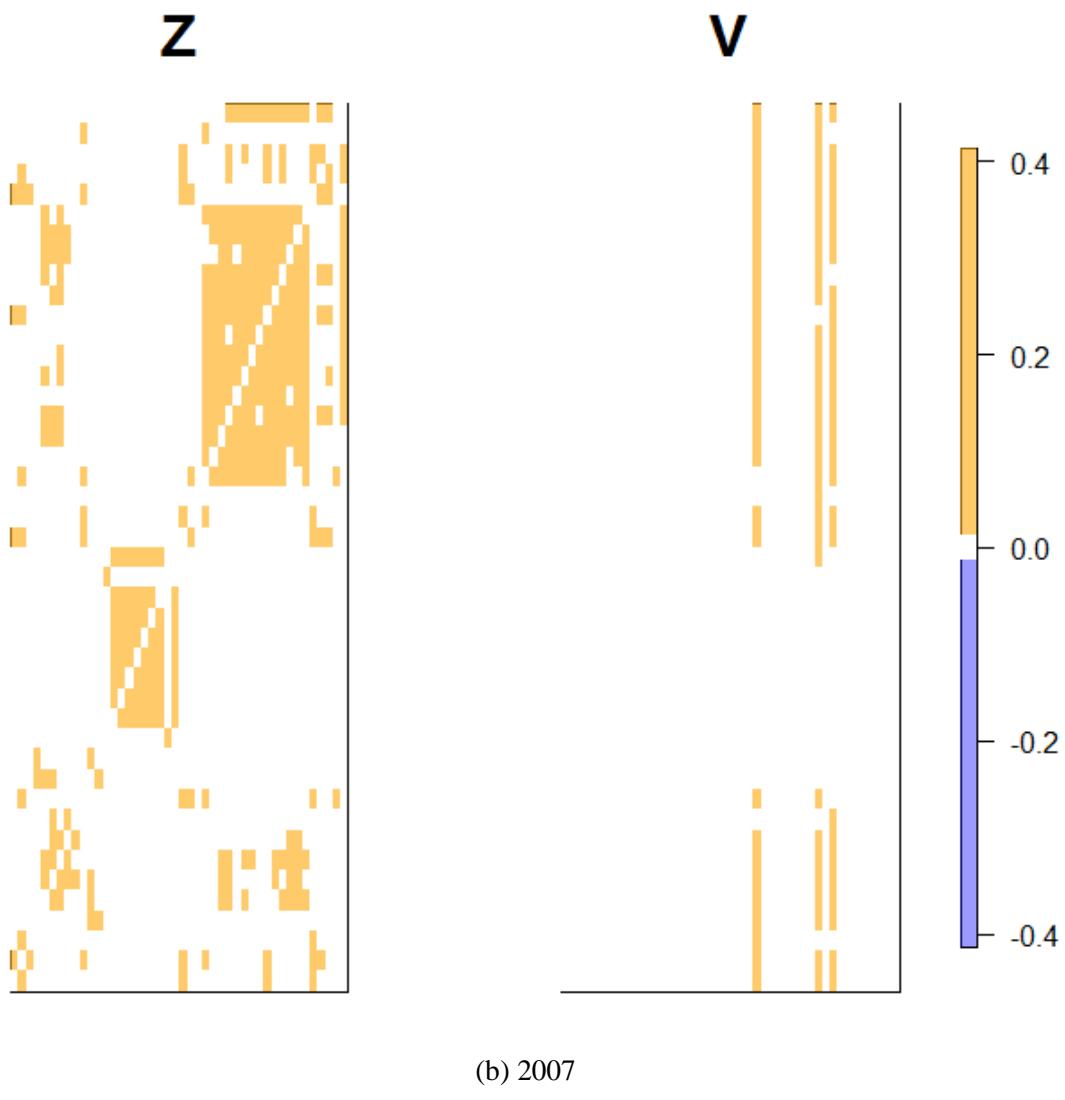


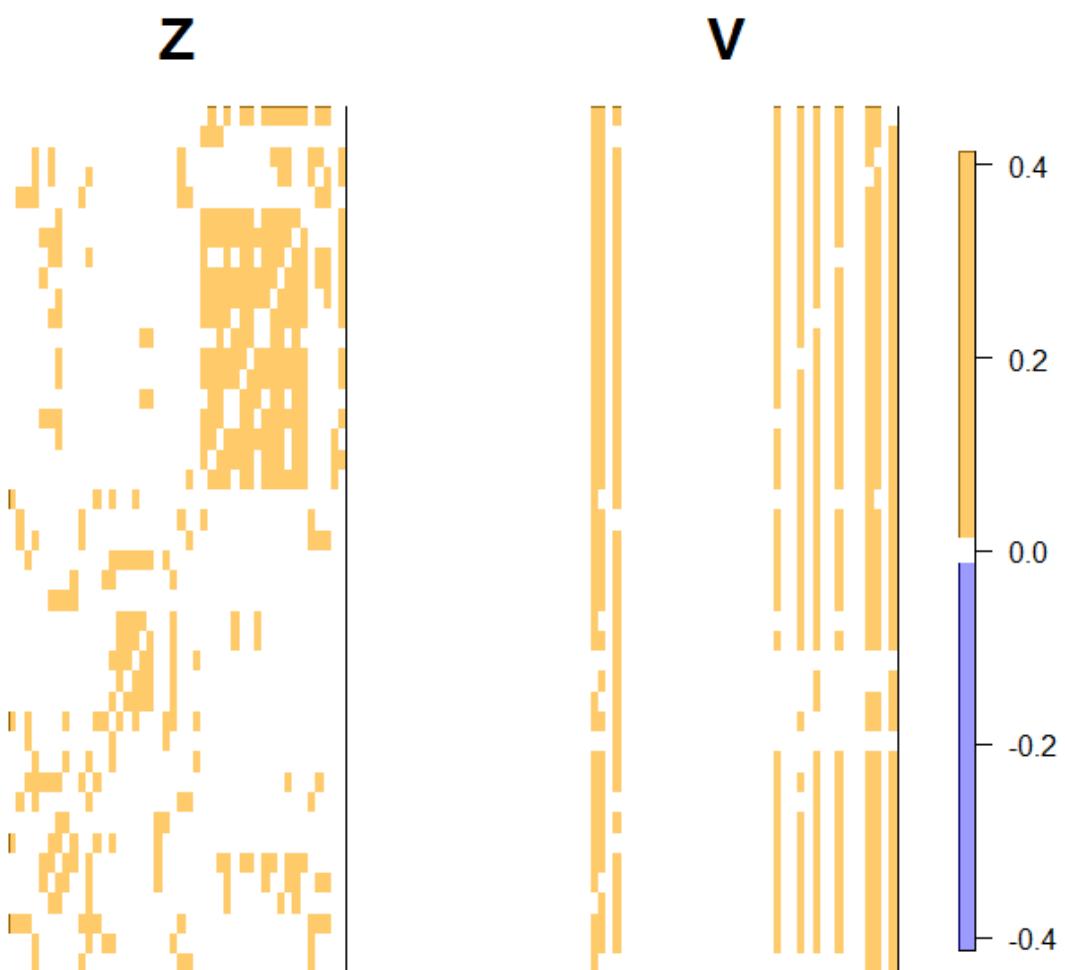
Appendix F. The heat maps of Z and V in hub covariance graph of 2002, 2007, 2012 and 2017.



(a) 2002

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(c) 2012

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